TECHNICAL REPORT 055

Ecological Resilience and Complexity:
A Theoretical Framework for Understanding and Managing British Columbia's Forest Ecosystems in a Changing Climate

2009

ADAPTING TO CLIMATE CHANGE

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MEMORANDUM

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Re: Errata – author missed

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At global, regional, and local scales, forest managers are faced with unprecedented pressures to supply forest resources for human consumption while still maintaining a diverse array of other ecosystem services essential to human well-being. While this alone has posed major challenges to forest management, global climate change presents a new range of daunting challenges. The potential for major ecosystem changes as well as uncertainties about the degree and rate of climate change necessitates a major shift in thinking about forest management.

Recent scientific literature proposes new approaches to forest management that focus on "managing for ecological resilience," with the idea that it provides a tenable framework for achieving sustainability goals when environments are changing and the future is uncertain. The concept of ecological resilience has been used to guide the management of ecosystems degraded by human land use activities, and managing for resilience is a commonly discussed approach for countering the negative impacts of climate change. This document summarizes the theoretical literature on ecological resilience and complexity, and describes how this evolving body of science can begin to guide the management of forest ecosystems in a changing climate.

Ecological resilience describes the capacity of ecosystems to absorb disturbance without collapsing into a qualitatively different state. While research is still under way to develop a structured understanding of the mechanisms regulating ecological resilience, scientists propose that key ecological processes, operating across varying scales of time and space (e.g., seedling survivorship, forest succession, periodic natural disturbances, propagule dispersal that facilitates species range shifts), generate the complexity needed to maintain ecosystem resilience to environmental change. Maintaining and enhancing biological diversity across multiple scales may play an important role in preserving ecosystem services if it generates redundancy in the ecological processes that confer ecological resilience (i.e., conserves key ecosystem functions).

Adapting forest management frameworks to climate change involves actions that minimize the risk of adverse climate-change impacts and capitalize on its benefits. Managing for resilience advocates diverse and novel actions that help cope with uncertainties about future forest conditions and reduce both societal and ecological vulnerabilities to climate change. While societal adaptations to climate change include the development of policies to encourage adaptation, modifying wood processing technologies, and revising expectations of resource use and conservation objectives, management to maintain ecological resilience involves deliberate, on-the-ground forest practices that maintain ecosystem complexity across multiple scales of time and space, and facilitate gradual ecosystem change in response to climate change. In this report, we present some examples of the kinds of on-the-ground actions that could be undertaken to begin the process of managing for ecological resilience to climate change. They include: facilitating tree species (and population) migration and range shifts; developing forest harvest, regeneration, and stand-tending activities that maintain or enhance ecosystem complexity and response diversity to environmental change, such as the forest structures generated by past disturbance regimes; planting broader mixes

of trees across landscapes to help reset successional trajectories; promoting landscape connectivity; and retaining or restoring areas that may be buffered against climate change. Managing for ecological resilience is in its infancy and the technical details about how to implement this new approach to forest management will depend on ecosystem type and evolve as the science integrating resilience, complexity, and biodiversity evolves and more information about the impacts of climate change on ecosystems becomes available through field monitoring programs and quantitative modelling research.

Resilience-based ecosystem management, especially when it takes into account changing climate conditions, represents a profound shift in the way the Ministry of Forests and Range will approach how forest ecosystems are managed, and poses challenges to many existing practices and policies in British Columbia. Involving a more diverse array of forest practices than traditional forest management approaches, it will require setting landscape-level management objectives for desired future forest conditions and making decisions regarding how to cope with unexpected and undesirable management outcomes. Transitioning to resilience-based ecosystem management also requires an understanding of complex ecological and social feedbacks, but an awareness of this, and an openness to work with complexity scientists, forest ecologists, climatologists, forest geneticists, and others can help to make this transition.

PREFACE

This Technical Report is one of a series of foundation papers for the British Columbia Ministry of Forests and Range's Future Forest Ecosystems Initiative (FFEI). The series of foundation papers will increase awareness about the potential impact of climate change on forest range resources in British Columbia. It will also provide information to help assess the vulnerability of British Columbia's forest and range resources to climate change and guide the development of adaptation strategies.

This report summarizes the theory of ecological resilience and explores how this aspect of complex system science provides guidance for managing forests in a changing climate.

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This report has undergone a succession of revisions based on input from a wide range of experts. We are grateful to Alvin Yanchuk, Dave Spittlehouse, and Evelyn Hamilton, who reviewed this document and provided guidance on its content. Discussions with Sybille Haeussler and Werner Kurz about the topic of ecological resilience and its applications in management were also a tremendous help. Discussions with other scientists and forest managers at two international conferences during the summer of 2008—the International Union of Forest Research Organizations (IUFRO) Climate Change and Forest Management Adaptation Conference (Umea, Sweden) and the IUFRO conference on biological diversity (Kamloops, B.C.)—contributed significantly to our "train of thought." Hamish Kimmins, Rachel Holt, Timothy Kittel, Gary Peterson, and Klaus Puettmann reviewed an earlier version of this document; their comments helped to improve the report. The FFEI technical team, including experts from a wide range of fields (e.g., forest health, fire protection, conservation, timber supply), provided input regarding the application of an evolving science to key natural resource management issues.

This document was produced with the support of our Chief Forester and members of the FFEI Management Team.

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1 INTRODUCTION

Forests cover about two thirds of British Columbia. From region to region and, over the province, these forest ecosystems provide a characteristic set of ecosystem services[1] important to the well-being of British Columbians (e.g., clean air and water, timber and non-timber products, cultural and spiritual inspiration). In British Columbia, and globally, the last 50 years have seen substantial changes in societal views about how forests should be managed. Shifts from sustained-yield to sustainable forestry, to convergence on sustainable forest management and ecosystem management reflect concerns about the maintenance of biological diversity, the disappearance of old forests, and a greater societal desire to increase the range of goods and services for which sustainability is sought (Canadian Council of Forest Ministers 2003; Gerardo et al. 2005; Papaik et al. 2008). These developments are especially prevalent on public forest lands, such as those in British Columbia, where scientists have long promoted an ecosystem approach to forest management (Pojar et al. 1987; Christensen et al. 1996; Kimmins 2004, 2008). Despite shifts in management paradigms over the last several decades, forest managers once again find themselves at an important crossroads because of global climate change.

While various global and regional efforts are under way to reduce greenhouse gas emissions, the cumulative impacts of past human activities mean that the current trajectory of climate change is fixed for several decades (Intergovernmental Panel on Climate Change 2007; Montenegro et al. 2007). Even if emissions were stabilized at 90% below present levels, temperatures would still increase by 2°C by 2050 (Weaver et al. 2007), and natural resource managers will need to plan for this kind of near-future change. Global climate change, however, does not only entail increases in air temperature but also changes in solar radiation and precipitation regimes, including the type (snow vs. rain), timing, amount, and interannual variability of precipitation (Barnett et al. 2005; IPCC 2007). Although the patterns of changing temperature and precipitation will vary from region to region in British Columbia, the province will have greater warming and precipitation changes than the global average (Spittlehouse 2008). Warming has already been greater in the northern parts of the province than in the southern and coastal regions, with minimum temperatures increasing faster than maximum temperatures (Rodenhuis et al. 2007; Spittlehouse 2008). While summer precipitation is expected to increase in the northern and coastal regions of British Columbia, the southern parts of the province are expected to be drier (Spittlehouse 2008). Extreme temperature and precipitation events are projected to be of greater magnitude and more frequent, increasing the intensity and duration of heat waves and drought and storm severity.

As species respond to changes in climate conditions that are outside the range of what they have been exposed to over the last several centuries (IPCC 2007; Spittlehouse 2008), the resulting ecosystem changes substantially increase the risk of losing valued ecosystem services. Although ecosystems possess an inherent capacity to evolve, or change, in response to climate variability, forests are unlikely able to evolve rapidly enough to keep up with the rate of climate change (Millar et al. 2007; Aitken et al. 2008). Moreover, the

1 See Appendix 1: A classification of ecosystem services.

legacies of past land use and continued pressures from forestry activities, land conversion to urban or agricultural uses, fragmentation from roads or other development, and exotic species invasions are making some ecosystems, and their services, more vulnerable to the effects of climate change (Turner et al. 1993; Woods et al. 2005; Carroll et al. 2006; Campbell and Carroll 2007). Given the potential for climate change to cause major ecosystem changes, an important shift in thinking about forest management is necessary. In particular, forest and land managers must consider how their practices must change to minimize the risk of undesirable future outcomes that could arise from having forests that are ill-adapted to future conditions (Holling and Meffe 1996; Costanza 2000a; Millar et al. 2007).

The Future Forest Ecosystems Initiative (FFEI) was initiated by British Columbia's Chief Forester to start the process of adapting British Columbia's forest and range management framework to a changing climate. Conditions in British Columbia's forest ecosystems are changing in ways that were not foreseen a decade ago. The purpose of this initiative is to expand our knowledge of the potential responses of ecosystems and their services to climate change, and to use this knowledge to adapt the current forest management framework, and its associated stewardship policies, to minimize the societal impacts of changing forest conditions. A central theme arising from this initiative is that British Columbia's forest management framework should be adapted to maintain or enhance the resilience of British Columbia's ecosystems as climate changes. Management that maintains or enhances ecosystem resilience to changing environments has received increasing recognition as a way to attain ecological, social, and economic sustainability goals. The concept of ecological resilience has been used to guide the restoration of ecosystems degraded by human land use activities, and managing for resilience is a commonly discussed approach for countering the negative impacts of climate change on ecosystems (Dale et al. 2001; Price and Neville 2003; Millenium Ecosystem Assessment 2005; McLeod and Salm 2006; Millar et al. 2007). The intent of this paper is to review the theoretical basis of a resilience-based approach to forest management and to provide some guidance about the kind of forest management practices that could enhance the resilience of ecosystems in the face of climate change and reduce the risk of rapid, unexpected ecosystem changes that generate major losses of ecosystem services.

2 ECOLOGICAL RESILIENCE

The concept of ecological resilience provides a theoretical framework for understanding how ecosystems change in response to local or regional disturbances as well as to large-scale perturbations like climate change. Drawing on sub-disciplines of ecology such as genecology, ecophysiology, population ecology, disturbance ecology, and landscape ecology, resilience theory was developed over the past three decades in an effort to explain abrupt and surprising ecosystem changes that can cause catastrophic impacts to ecosystem services (Gunderson et al. 2009).

Theoretical ecologists define resilience as: "the capacity of ecosystems to absorb disturbance without collapsing into a qualitatively different state that

is controlled by a different set of [ecological] processes" (www.resalliance.org/567.php).[2] This definition of ecological resilience is used synonymously with the term *ecosystem resilience* and many ecologists interpret this to mean: (1) the capacity of an ecosystem to resist change; (2) the amount of change an ecosystem can undergo and still retain the same controls on structure; and (3) the ability of an ecosystem to reorganize following disturbance (Holling 1973; Levin 1998; Gunderson and Holling 2002; Folke et al. 2004; Brand and Jax 2007).

Throughout the ecological literature, *ecological resilience* is often used interchangeably with *ecosystem adaptability* (e.g., Gunderson and Holling 2002; Levin 2005; Puettmann et al. 2009). Ecosystem adaptability, in a way, is analogous to Darwinian evolution of species. In this view, the various structures, compositions, and ecological processes of ecosystems are constantly changing in response to environmental change. Ecosystems, however, are not adaptive entities in the Darwinian sense, and do not evolve as a unitary whole, as do species. Rather, changes in properties of ecosystems are dependent on the capacity of their components—individuals, populations, and species—to adapt to changing environments. Similarly, using *resilience* to describe the capacity of individuals, populations, and species to adjust to their environment is equally problematic because, in this situation, resilience is being used to describe Darwinian adaptation. In this paper, we make an important distinction between ecological resilience and adaptability: we refer to *ecological resilience* as an ecosystem property, and *adaptability* as a characteristic of individuals, populations, and species.

2.1 Theoretical Models of Ecological Resilience

The "ball-and-basin" model of ecosystem change (Figure 1) is one theoretical model commonly used to depict the concept of resilience (Orians 1975; Scheffer et al. 2001; Scheffer and Carpenter 2003). It shows how ecosystems may shift into a different state or "alternative domain of attraction." A "domain of attraction" is represented by the basin in which the ecosystem moves around like a rolling ball with the number of possible positions of the ball in the basin representing the degree of variability in an ecosystem's structure (e.g., shifting stand age and forest patch-size distributions across landscapes). Small disturbances will temporarily move the ball but it will drift back towards the bottom of the basin; the speed at which the ball moves to the bottom of the basin is referred to as ecosystem *elasticity* or *recovery time*.[3] If the shape of the cup, which reflects ecosystem resiliency, is altered, or if the ball is "knocked" hard enough by a major external disturbance, the ball (i.e., the ecosystem) can move out of its current basin to an alternative domain of attraction. Movement to another basin represents the crossing of a threshold to a new ecosystem state, like a shift from woodland to grassland ecosystems that could be caused by repeated fire, drought, and insect disturbances in a warmer, drier climate, or a highly undesirable shift from woodlands to a degraded ecosystem state dominated by invasive species (McDougall and Turkington 2005).

2 *Resilience* is defined in two different ways in the ecological literature, reflecting different aspects of ecosystem stability. See Appendix 1 for details.

3 This has also been defined as *engineering resilience*. See Appendix 2: Engineering resilience vs. ecological resilience.

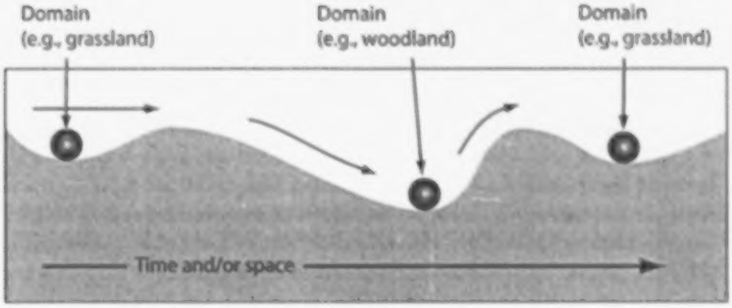

FIGURE 1 *Ball and basin model of ecosystem change.*

The four-phase adaptive cycle of ecosystem dynamics is another conceptual model of ecological resilience (Gunderson and Holling 2002) (Appendix 3). A major but often unpredictable disturbance can rapidly initiate the first phase, referred to as the *release phase*. In this phase, important ecosystem components (e.g., forest floor, shrubs, trees, wildlife habitat) are lost and resources become available. This new flush of resources leads to the *reorganization phase* where new populations and species may colonize disturbed parts of the ecosystem and establish if they can invade and adapt to post-disturbance environments. Small differences in starting conditions during the reorganization phase (e.g., relative species abundance or climate/weather) can generate major differences in ecosystem development. The reorganization phase then transitions to the *growth phase* marking another trip through the previous adaptive cycle (e.g., repeated fire in lodgepole pine ecosystems), or the beginning of a new and qualitatively different adaptive cycle. A new adaptive cycle represents a loss in ecosystem resilience, a movement towards an alternative "domain of attraction," and therefore a shift in ecosystem state. Even if small temporal differences in starting conditions are not large enough to generate a major shift in ecosystem state, the spatio-temporal variability in starting conditions, particularly those generated by variability in the type, timing, and intensity of disturbance, can drive the development of multiple successional pathways from the growth phase to the last phase of the adaptive cycle, the *conservation phase* (e.g., Fastie 1995; Frehlich and Reich 1998; Donnegan and Rebertus 1999; Campbell and Antos 2003; Kipfmueller and Kupfer 2005). This results in asynchronous forest ecosystem development and therefore a range of ecosystem structures in landscapes over space and time (e.g., varied forest age-class distribution and patch size) that is often referred to as the "natural" or historic range of ecosystem variability. This diversity in structure can have important implications for ecological resilience, in particular, an ecosystem's vulnerability to subsequent disturbances and its capacity to recover/reorganize following disturbance (Peterson 2002; Campbell et al. 2008). Subsequent disturbances can occur at any time during the ecosystem recovery process (i.e., from the growth to the conservation phases), the rate of which depends on rates of post-disturbance succession.

Of particular concern are the compounding effects of multiple disturbances. Resilience erodes if ecosystems are continuously unable to recover before another disturbance occurs because ecological "memory" is lost (e.g., seedbanks, soil microbes) (Peterson 2002). The cumulative effects of human disturbances can have profound impacts on ecosystem structure and dynam-

ics (e.g., Kimmins 2004). For instance, it is assumed that human activities generating forest structures (e.g., forest age-class distribution) substantially different from those generated by historical disturbance regimes will decrease the likelihood that an ecosystem will remain within a particular domain of attraction.

2.2 Mechanisms of Ecological Resilience

Ecologists have suggested for some time that ecological resilience arises from the interactions among ecological processes that are fast and localized and processes that are slower but occurring at a larger spatial scale (Carpenter and Levitt 1991; Levin 1992). However, research to develop a structured understanding of resilience is still under way (e.g., Rietkerk et al. 2002; Gunton and Kunin 2007; Chalcraft et al. 2008; Suding et al. 2008). Holling (1992) described four major scales of ecological processes for forests: (1) small and fast scales where biophysical processes regulate plant physiology and morphology and determine year-to-year establishment, growth, and survivorship of individuals; (2) larger and slower scales where patch dynamics, interspecific competition for nutrients, light, and water influence local species composition and regeneration in stands over decades; (3) still larger and slower scales, including meso-scale processes such as fires, storms, insect outbreaks, and large-mammal herbivory that drive succession and determine forest structure over tens of metres to kilometres and over decades to centuries; and (4) the largest scales where climate, geomorphological, and biogeographical processes (e.g., local extinction, migration, colonization) determine species distributions and forest landscape patterns across hundreds of kilometres and over millennia. Further work suggests that ecological resilience is regulated by a small set of key processes (also frequently called *key controlling variables* or *key ecosystem functions*) operating at characteristic periodicities and spatial scales (Peterson et al. 1998; Gunderson and Holling 2002). Gunderson and Holling's (2002) hierarchical model of ecosystem dynamics ("panarchy") suggests that ecological resilience is regulated by two types of cross-scale feedback loops. The first kind of cross-scale feedback loop represents interacting ecological processes that generate the spatial diversity in ecosystem structures needed to facilitate asynchronous small-scale disturbances and prevent catastrophic ecosystem losses from a single future disturbance event (e.g., variability in stand vulnerability to insect or disease outbreaks that reduce the risk of severe and widespread outbreaks across landscapes). The second kind of cross-scale feedback loop represents larger and slower ecological processes that conserve or destroy biological legacies needed for ecosystems to reorganize after local disturbances (e.g. migration of populations or species to suitable habitat). These feedback loops, or mutually reinforcing forest structures and processes, are a key aspect of ecosystem dynamics and ecological resilience (Peterson 2002). Negative feedbacks tend to maintain resilience because they inhibit or dampen ecosystem changes, and positive feedbacks tend to destabilize ecosystems because they accelerate or amplify ecosystem changes.

The role that biological diversity plays in conferring ecological resilience continues to be a topic of intense debate (McCann 2000; Levin 2002; Ives and Carpenter 2007; Wilmers 2007). Contemporary theoretical ideas revolve around the importance of functional redundancy and response diversity (Peterson et al. 1998; Diaz et al. 2003; Elmqvist et al. 2003). Some argue that ecosystems contain groups of species that perform essentially the same ecosystem functions, such as fixing nitrogen, dispersing seeds, decomposing

soils, cycling biomass, and regulating hydrological or disturbance cycles (Brown and Heske 1990; Körner 1993; Prins and Van der Jeud 1993; Jones et al. 1994; Naiman et al. 1994; Nowacki and Abrams 2008; Suding et al. 2008). Thus, the loss of one member of a group is unlikely to have major ecosystem impacts because others will continue to perform the same function (i.e., functional redundancy) (Folke et al. 2004). However, functional redundancy alone will not guarantee ecological resilience. Members of these functional groups must also respond differently to environmental change. Therefore, response diversity conveyed through variability in genes, populations, and species across forest landscapes could contribute to ecological resilience. Ives and Carpenter (2007) argue, on the other hand, that biological diversity, or response diversity, alone is rarely a primary determinant of ecological resilience. Rather, the role of biological diversity may be critical for generating redundancies in the key ecological processes that operate across temporal and spatial scales to regulate ecological resilience (Peterson et al. 1998; Loreau et al. 2002). However, as our knowledge of these processes is often incomplete, and in the face of uncertain environments, a precautionary approach suggests maintaining, or enhancing, as much diversity as possible (Namkoong 2005).

2.3 Non-linear Relationships, Ecological Thresholds, and Irreversible Ecosystem Change

The development of strong non-linear relationships or the crossing of critical ecological thresholds can result in the loss of ecological resilience and irreversible ecosystem change. Non-linear relationships occur when variation in one factor affects another in a disproportionate way. They are more often the rule rather than the exception in biological systems (Hilbert 2002). Examples of non-linear relationships in forest ecosystems include: seedling abundance for a particular species decreasing exponentially with distance from seed sources, forest litter production increasing with increasing distance from a tree but then decreasing with greater distance, and cyclical relationships between predator and prey populations. Non-linear relationships may also show threshold patterns where the initial effects of environmental change are small but the cumulative effects have much greater impacts. In forests, losses of wildlife habitat across landscapes may have little effect on populations until a critical threshold is reached, at which point any more habitat loss causes rapid population reductions and local extinctions (e.g., Dykstra 2004).

Ecological thresholds are determined by the biotic and abiotic factors that limit the persistence of individuals, populations, and species. Environmental change that causes maladaptations and local extinctions of species, and alters key ecological processes and feedback loops, may have cascading effects that destabilize ecosystems (Burkett et al. 2005; Ims and Fugeli 2005; Ims et al. 2007). However, ecosystem responses to environmental change may be largely undetectable until a threshold is reached, at which time an abrupt, large, unexpected, ecosystem shift occurs. A characteristic feature of ecological thresholds is *hysteresis*, which means that ecosystem change may be irreversible once a threshold is crossed, even if the driving force that generated the threshold behaviour ceases (Scheffer and Carpenter 2003). Global climate change and biodiversity declines could generate irreversible change (Folke et al. 2004; Fagre and Charles 2009).

Abrupt and unexpected ecosystem shifts, many of which have been induced by humans, are described for many terrestrial ecosystems (Gunderson and Holling 2002) and they inevitably lead to resource management crises.

Understanding the conditions under which thresholds are likely to be crossed, and what mechanisms underlie the threshold behaviour, is critical to managers (e.g., Hagerthey et al. 2008). Although it remains quite difficult to identify specific thresholds of ecosystem change, detailed process-based ecosystem research that identifies and studies critical species interactions and feedback loops, coupled with non-linear scenario modelling of key ecosystem responses to environmental change, could provide valuable insight (Kimmins et al. 1999; Walker and Meyers 2004; Gronffman et al. 2006; Kimmins et al. 2008).

3 COMPLEXITY

Complexity theory was developed from key ideas in economics, physics, biology, and the social sciences and contributes to important new concepts for approaching issues of environmental sustainability such as resilience, scaling, and non-linear ecosystem dynamics (Anderson 1972; Waldrop 1992; Chikumbo et al. 2001; Burkett et al. 2005; Green et al. 2006; Norberg and Cumming 2008; Puettmann et al. 2009). The science of complexity is not a discipline per se, but a set of theoretical frameworks that apply to systems in a wide variety of fields. Complex systems science provides a framework for describing complex systems mathematically and tools for modelling their dynamics.

A better understanding of how complexity arises, and an improved ability to forecast how complex systems such as forest ecosystems respond to both natural and human-induced change, is an increasingly critical aspect of improved ecosystem stewardship and sustainability (Kimmins 2008). Conceptualizing ecosystems as complex systems, and drawing on an array of fundamental ecological concepts and theories from complex systems science, provides a framework for thinking about ecological resilience (e.g., Kaufmann 1993; Holling 2001; Gunderson and Holling 2002; Scheffer and Carpenter 2003; Levin 2005; Solé and Bascompte 2006).

Complex systems science as applied to ecological systems strives to understand how ecosystems are organized, how interactions among the individual parts or processes give rise to system-level properties, and how ecosystems change in response to variations in environmental conditions. Ecosystems of all types can be conceptualized as *complex systems* or, as they are called by evolutionary biologists, *complex adaptive systems* (Levin 1998, 2002). Forest ecosystems, being complex systems, have the following key characteristics:

1. they are made up of many parts (trees, small mammals, birds, insects, soils, etc.) and processes (mortality, succession, disturbance cycles, nutrient cycling, species migration, etc.) that interact with one another and their environment over multiple scales of time and space;
2. these interactions, which give rise to heterogeneous forest structures, may range from strong and direct to weak and diffuse and can be modified by negative or positive feedback loops with the environment to stabilize or destabilize ecosystems;
3. feedback loops may be non-linear, which means that small differences in starting conditions following disturbance could cause large, unexpected, and unpredictable changes in ecosystem structure and development;
4. forest ecosystem boundaries are difficult to determine and are open to influences outside the system;

5. forest ecosystems have "memory," which means that biological legacies of previous states influence present and future states; and
6. forest ecosystems are made up of smaller units of biological organization (i.e., individuals, populations, species, communities) that are also complex systems.

Complexity science suggests that the attributes of forest ecosystems are never highly predictable based merely on knowledge of their individual parts—while qualitative forecasts may be possible, complexity makes it very difficult to make precise quantitative predictions of ecosystem-level attributes such as total biomass, species composition, forest structure, productivity, and resilience. Having a strong basis in evolutionary theory, complex systems science also suggests that variability in ecosystem parts and ecological processes may play a role in how ecosystems respond to changing environmental conditions (Levin 1998, 2005).

Conceptualizing ecosystems as complex systems is a relatively recent development in the field of ecology (Gunderson and Holling 2002; Levin 2005; Green et al. 2006; Solé and Bascompte 2006) and represents a substantial shift in thinking away from traditional reductionist science. Even basic ideas on how to study ecosystems require rethinking when ecologists view ecosystems as complex systems. Ecologists are recognizing more and more that understanding the mechanisms and ecological processes that contribute to ecosystem-level properties, especially ecological resilience, is of critical importance for an ecosystem approach to forest management.

4 MANAGING FOR ECOLOGICAL RESILIENCE AND COMPLEXITY

Managing for ecological resilience advocates practices that maintain or enhance the ability of ecosystems to cope with change. Ecologically based natural resource management should maintain the inherent complexity of ecosystems and therefore ecosystem *response diversity* to environmental change, so that ecosystem vulnerability to any single future disturbance event is low and the potential to reorganize following disturbance remains high (Chapin et al. 1997; Gunderson and Holling 2002; Elmqvist et al. 2003; Folke et al. 2004; Gunderson et al. 2009). Complex systems science and resilience theory suggest that ecosystems should be managed within the context of the key ecological processes that control ecological resilience (Bennett et al. 2005; Cummings et al. 2005). For example, by maintaining a robust foodweb that had a diversity of fish species with different responses to changes in nutrient levels of freshwater lake ecosystems, resource managers were able to prevent sudden shifts to an undesirable ecosystem state where algal blooms occurred (Carpenter and Kitchell 1993).

One of the most significant contributions of complex systems science and resilience theory is the importance of scale, particularly how the interaction of ecological processes across scales is important for ecological resilience and the maintenance of ecosystem services. Every ecosystem, the ecosystem services it provides, and the ecological processes that regulate them occur at characteristic spatial scales ranging from micro-scale (e.g., the proportion of a stand that provides habitat for an endangered shrew), to stand scale (e.g.,

timber production), to watershed scale (e.g., salmon habitat), to landscape scale (e.g., visual quality, carbon sequestration, species migration) (Hann et al. 2001; Puettmann et al. 2009). British Columbia's Biogeoclimatic Ecosystem Classification (BEC) (Pojar et al. 1987; Meidinger and Pojar 1991) provides a fundamental framework for identifying ecosystems and ecosystem services at different scales (e.g., BEC zone, subzone, site association). The importance of scale to managing for resilience means that response diversity within and over a range of spatial and temporal scales is required to maintain an array of ecosystem services now and for future generations. Generating such diversity necessitates planning and the setting of management objectives over landscapes, with measures for desired management outcomes that include the desired future forest ecosystem condition (Chikumbo et al. 2001; Lohele et al. 2002; Puettmann et al. 2009).

The application of complex systems science and resilience theory to forest ecosystem management centres on two main points:

1. that resilience is a property of complex systems, which means that complexity at a hierarchy of scales is a highly desirable attribute to maintain the capacity of ecosystems to gradually change in response to changing environmental conditions and provide benefits to future generations, and
2. that the inherent complexity of ecosystems means that forest development could proceed down a number of paths, depending on external influences, such as climate change, and generate a range of outcomes but no single, predictable forest condition.

A resilience-based approach to forest ecosystem management captures these characteristics of complex systems and represents movement towards improved forest stewardship because it promotes a potentially more diverse array of forest practices than traditional management approaches that not only helps generate response diversity to future disturbances and environmental change but also generates the complexity needed to sustain a range of ecosystem services. More diversity in practices over landscapes means that while the advantages of some traditional management approaches may be lost at the stand level, new benefits and opportunities may emerge. For example, more diverse reforestation practices that generate variation in stand management outcomes over landscapes may generate greater variability in timber growth and yield but, as a tradeoff, these new forest landscapes may be less vulnerable to future disturbance (Drever et al. 2006). In British Columbia, fire exclusion, forest harvest patterns, reforestation practices, cattle grazing, exotic species invasions, and climate change have altered many ecosystems. For example, the cumulative effects of fire suppression, forest regeneration practices, and climate change have contributed to the homogenization of some interior forest landscapes, making natural pine forests highly vulnerable to expanding mountain pine beetle outbreaks and pine plantations highly vulnerable to a novel *Dothistroma* needle blight epidemic (Taylor et al. 2005; Woods et al. 2005; Carroll et al. 2006). The unexpected extent of lodgepole pine mortality led to major and unexpected losses of many valued ecosystem services, including timber, wildlife habitat, water quality, visual quality of landscapes, and carbon sequestration, which in turn may contribute to an increase in the rate of global climate change (Kurz et al. 2008b).

Through the application of more diverse practices across landscapes, a resilience-based approach to forest management forms the underpinnings of active adaptive management,[4] with the possibility of learning from and responding to unexpected outcomes of various practices. Forest management frameworks will need to be flexible enough to allow for diversity and promote experimentation, learning, and subsequent adjustment in the event of surprising management outcomes.

Scientists have long recommended the use of information about the range of historical forest structures (e.g., stand density, size, age-class distribution over landscapes) to make decisions about the array of practices needed to structure forest ecosystems now and into the future (Bergeron et al. 1999; Landres et al. 1999; Millar and Woolfenden 1999; Bergeron et al. 2006; Thompson et al. 2006). Typically, pre-European settlement forest structures, which overlap with the Little Ice Age (1300–1850) have been the desired management targets. In British Columbia, these ideas have been translated into management through the promotion of practices that preserve the historic range of biological diversity and mimic forest structures generated by historical disturbance regimes (e.g., British Columbia Ministry of Forests 1995; Wong and Iverson 2004). For some ecosystems in British Columbia, historical forest structures may provide useful guidance for future forest management. For example, the forests of southeast Alaska and north coastal British Columbia remained coniferous forests dominated by western redcedar, western hemlock, and Sitka spruce, despite periods of considerable climate change over the last several millennia (Alaback 2009). This suggests that moving these wet coastal forests away from their historical structures—for example, converting landscapes dominated by old-growth forests to landscapes dominated by second-growth forests—could make these forest ecosystems more vulnerable to the adverse effects of climate change, including insect outbreaks. Winchester (1998) suggests that the risk of insect outbreaks may be lower in old-growth coastal forests than in second-growth coastal forests because they contain much higher densities of predators and parasitoids of potentially damaging herbivorous insects. For other ecosystems, however, guidance based on the historical range of variability in forests structures alone is unlikely sufficient for implementing resilience-based management when the climate is changing. As greenhouse gas emissions push regional climates well beyond historical boundaries (IPCC 2007), especially for interior and south coastal British Columbia, ecosystems of the past are becoming increasingly tenuous management targets. Management geared toward maintaining historical forest ecosystem conditions in these ecosystems may require more effort by managers and could generate forests ill-adapted to current and future conditions and prone to undesirable outcomes (Holling and Meffe 1996; Millar et al. 2007). Rather than being management targets, historical information is valuable for understanding responses of species and ecosystems to past climatic variability and this knowledge can be used to make projections about plausible future forest conditions, such as the potential impacts of climate change on the adaptability of local populations and the

4 Adaptive management is a systematic process for continually improving management policies and practices by learning from the outcomes of a operational programs. "Active" adaptive management employs management programs that are designed to experimentally compare a number of selected policies or practices, by evaluating alternative hypotheses about the system being managed.

expansion and contraction of species ranges (Woods et al. 2005; Carroll et al. 2006; Hamann and Wang 2006; Rehfeldt et al. 2006; McKenney et al. 2007). This range of plausible future forest conditions, in the form of probability distributions about the impacts of climate change on ecosystem attributes and ecosystem services (e.g., Davis et al. 1998; Prato 2007, 2008), will help determine the range of practices needed to maximize the chances of attaining ecological, social, and economic sustainability goals in a changing climate.

Resilience-based ecosystem management, especially when it takes into account changing climate conditions, represents a profound shift in the way the Ministry of Forests and Range will approach how forest ecosystems are managed and poses challenges to many existing practices and policies in British Columbia. However, an awareness of, and openness to work with, complexity scientists, forest ecologists, climatologists, forest geneticists, and others can help to make this shift (Puettmann et al. 2009).

5 FOREST MANAGEMENT IN A CHANGING CLIMATE

5.1 The Complexities of Ecosystem Response to Climate Change

Climate change is expected to have impacts on most ecological processes that influence ecosystems. Changes in temperature and precipitation regimes affect the growth, reproduction, and regeneration of trees and other plants, which alter plant community successional trajectories and the quality or quantity of wildlife habitat (Root et al. 2003). Climate change is also expected to alter historical disturbance regimes involving fire (Flannigan et al. 2000; de Groot et al. 2003), insect outbreaks (Volney and Fleming 2000; Carroll et al. 2006; Gray 2006), forest disease (Woods et al. 2005); wind, floods, and drought (Dale et al. 2001), and modify soil processes, nutrient cycling (Swift et al. 2004), and hydrological cycles (Stewart et al. 2003). As a result of all these individual effects of climate change, and their interaction, species ranges will expand or contract, the geographic location of ecological zones will shift (Hamman and Wang 2006; Rehfeldt et al. 2006), forest ecosystem productivity will change (Boisvenue and Running 2006), and ecosystems could reorganize following disturbances into ecological systems with no current analogue (Hobbs et al. 2006; Rehfeldt et al. 2006; Williams and Jackson 2007).

The ecological processes that interacted over time and space to determine ecosystem properties such as resilience varied within fairly well understood boundaries called the "natural" or historical range of variability. However, there is a high degree of uncertainty about future forest conditions because of the responses of ecosystems to climate change. Temporal lags in ecosystem responses to climate change (Davis 1986), feedback loops, and non-linear threshold responses to climate change make it difficult to predict climate-change impacts. Rapid and unexpected changes could be triggered by even small changes in climate, if species thresholds are exceeded, because these threshold responses may alter feedback loops and have cascading ecosystem effects. For example, variability in the timing of responses to climate change among different taxonomic groups is likely to decouple species interactions and interdependencies, affecting ecological processes such as pollination, insect population control by parasitoids (or birds), predator–prey relationships, forest succession, and ecosystem recovery from disturbance. The impacts of human activities on landscapes introduce another level of complexity; they

can alter the rate or direction of ecosystem response to climate change in ways that are currently uncertain and unpredictable.

Forest ecosystems are already responding to climate changes that have occurred over the last few decades (Dale et al. 2001; Parmesan and Yohe 2003; Woods et al. 2005). Although complex systems such as forest ecosystems possess an inherent capacity to evolve in response to environmental variability, the rate at which they can respond to global climate change may be unacceptably slow, generating undesirable consequences for society. Forest management can begin to influence the direction and timing of ecosystem changes in some locations (Spittlehouse and Stewart 2003), and reduce the risk that climate change will generate rapid and unexpected ecosystem changes.

Lag effects in species responses to climate change means that management to cope with the effects of climate change on ecosystems may already be behind, and adapting forest management to minimize the negative impacts of climate change on ecosystem services can begin now. For example, empirical population genetics indicate that most forest tree populations are non-optimal for their current environments and in a state of "adaptational lag" (Namkoong 1969; Wu and Ying 2004). In British Columbia, small changes in seed transfer standards that address elevational lags in trees species adaptability are currently under way (O'Neill et al. 2008b).

5.2 Managing for Ecological Resilience

Adapting to climate change involves actions that minimize the risk of adverse climate-change impacts and capitalize on its benefits. Managing for resilience advocates novel and diverse forest management actions that help cope with the uncertainties about future forest conditions and could reduce both societal and ecological vulnerabilities to climate change (Spittlehouse and Stewart 2003; Spittlehouse 2005). Societal adaptations to climate change include the development of forest management policies to encourage adaptation, using more salvage wood, modifying wood processing technology, and revising expectations of resource use and conservation objectives. Forest management to enhance ecological resilience involves deliberate, on-the-ground, forest management actions to facilitate gradual ecosystem responses to climate change. The rest of this section outlines how adaptations to British Columbia's current forest practices could contribute to the goal of enhancing ecological resilience.

The long-term goal of managing for ecological resilience to climate change is to implement forest management practices that minimize the risk of rapid, unexpected ecosystem changes that could generate negative socio-economic pressures. Climate-induced changes to historical disturbance regimes are expected to have the most widespread and rapid ecological impacts on our forests (Dale et al. 2001; Westerling et al. 2006; Kurz et al. 2008b), and an important part of future forest management may need to focus on reducing ecosystem vulnerability to disturbances. In the short term, however, legacies of past management could generate a succession of forest disturbances that we are yet unable to anticipate or control. Given the degree of anticipated change, it will also be necessary to make decisions about fire protection activities and the way timber is extracted from forests, including the timing and location of logging, the silviculture systems used, the rate of harvest (i.e., rotation lengths), and what populations or species of trees will be used to reforest logged sites. Recognizing that ~1% of the harvestable forest landbase is

harvested in any year, our ability to maintain ecological resilience of British Columbia's forests through changes in forestry practices will initially be somewhat limited. However, our expectation is that we can have more impact over the longer term.

While forest management practices have a major impact on landscapes in British Columbia, the ecological resilience of forest landscapes and the services they supply to society may also depend on the future conditions of forests and non-forested ecosystems in the landbase where no forestry activities occur, the non-harvestable landbase (including parks, ecological reserves, wilderness areas, and areas with operational harvesting constraints). Therefore, ecological resilience to climate change cannot be achieved merely by adjustments we make to the harvestable landbase. It must also take into account forest conditions in the non-harvestable landbase because:

1. the non-harvestable landbase is integrated within the broader landscape and interacts with areas under forest management through feedback loops (e.g., interactions among forest structures and disturbance severity) and flows across landscapes (e.g., water, seed dispersal);
2. at broad (e.g., regional) scales, ecosystem processes and dynamics are a function of the entire landbase, whether affected by forestry, mining, agriculture, settlements, or protected areas;
3. management activities in the harvestable landbase may have direct impacts on the non-harvestable landbase (e.g., road building, disturbances such as fire, windthrow, insect outbreaks, and pathogens) and vice versa (e.g., fire suppression in protected areas);

Below we present some examples of the kinds of activities that could be undertaken in the forest landscape to enhance ecological resilience. The examples do not represent an exhaustive list of what could be done and while many examples involve silvicultural activities and tree species, we recognize that resilience-based ecosystem management will need to draw on a diverse array of practices that maintain other ecologically important species and ecosystem functioning (*sensu* Loreau et al. 2002). Moreover, the specific kinds of activities applied will vary with ecosystem type. As such, the following should not be interpreted as an invariable, and prescriptive, "cookbook" for managing British Columbia's forest ecosystems now and into the future. They merely represent the current scientific thinking about the generalities of managing forests when the climate is changing. Our ideas, and the technical details, about how to implement complex systems science and resilience theory into management will evolve as the science develops further and as new information about the potential impacts of climate change are obtained through modelling, experiments, and field observation. We also recognize that it may be several years before some of these actions can be operationally implemented on the ground.

5.2.1 Reduce ecosystem vulnerability to future disturbance In a changing climate, reducing forest vulnerability to future disturbances will be an important aspect of maintaining ecosystem resilience. Specific management activities may vary with ecosystem type. Below are some examples of general management actions that could help forest ecosystems build resilience to future disturbances:

- introducing fire into ecosystems where historical fire cycles have been disrupted by past fire exclusion and made them more vulnerable to severe future fires.
- developing forest harvest and regeneration patterns that generate a diversity of stand ages and compositions over landscapes to reduce forest vulnerability to future insect and disease outbreaks (Woods et al. 2005; Carroll et al. 2006; Campbell et al. 2008).
- varying the shape and size of clearcuts, and leaving patches or stream buffers to reduce vulnerability to potential for increased windthrow disturbance (e.g., Kimmins 2004).
- using alternative harvest systems—for example, warmer winters and increased winter precipitation may alter site hydrology, reducing access for winter logging, which normally helps reduce soil compaction (Spittlehouse and Stewart 2003). Also, alternative partial harvest systems, and various silviculture techniques, could be used to generate microenvironment changes (e.g., changes in snowmelt patterns, exposure) to facilitate the re-establishment of species that would otherwise be ill-adapted to regenerate in a new climate.
- planting species mixes that occur following natural disturbance—avoiding practices that generate uniform post-disturbance stands that may be highly vulnerable to future disturbance (British Columbia Ministry of Forests and Range 2007).
- reducing the effects of invasive species—warmer climates are apt to increase the spread and establishment of invasive plants, which may be tenacious competitors with planted seedlings or other early seral vegetation that provides valuable animal habitat (Floyd et al. 2006; Vila et al. 2007).
- planting resistant genotypes—breeding and using resistant planting stock may help protect against the anticipated expansion of certain insect and disease outbreaks.

5.2.2 Facilitate migration and species range shifts During historical warming periods, tree species range shifts in British Columbia occurred over long periods of time (e.g., Hebda 1995; Brown and Hebda 2003). Recent bioclimatic envelope modelling indicates that climatically suitable habitat for British Columbia trees will shift along major climatic gradients, upward in elevation and as far north as 700 km by about 2080 (Iverson and Prasad 2002; Iverson et al. 2004; Hamman and Wang 2006; Rehfeldt et al. 2006; McKenney et al. 2007). Warmer climates are projected to generate more suitable higher-elevation habitat for species that were previously restricted to lower elevations (Hamman and Wang 2006). Major diebacks caused by drought along the southern and warmest margins of species ranges, and expanding biotic disturbances, are expected to generate some northward tree species movements (Breshears et al. 2005). Many tree species, however, will be unable to migrate at a pace matching the current rate of climate change (Iverson et al. 2004; Aitken et al. 2008). Forest management could be used to speed up the migration process of forest trees and help forest ecosystems respond to the effects of rapid climate change by:

- planting seedlings from a range of seed sources, particularly from more southern or lower-elevation populations—this could help maintain productive forests of the same species while the climate changes and local

seed sources become less well adapted to new environments (Wang et al. 2006; O'Neill et al. 2008a, 2008b).

- planting logged sites with species expected to be adapted to the new climate (Rehfeldt et al. 2006; Millar et al. 2007; O'Neill et al. 2007). This could include planting species that have historically occurred south of the British Columbia border.
- banking surplus seed—broader use of non-local seed sources may require the procurement and banking of many different seedlots (Ledig and Kitzmiller 1992).

Projected shifts in tree species ranges provide information about where species and populations could be planted. Similarly, model projections can also be used to assess the climate migration distance that will minimize maladaptation risk over a rotation period. Results from experimental species transplant trials, which test species tolerance limits across a wide range of climates, will guide the planting of species best adapted to future climates throughout British Columbia (e.g., O'Neill et al. 2007). Moreover, strategic province-wide monitoring programs that identify where species are experiencing stress and dying will provide evidence about emerging directions in species range shifts and also help to identify local responses to climate change that projection models cannot detect.

There is widespread evidence that many species' ranges—not just trees—are shifting toward higher elevations and latitudes as the climate warms (Parmesan et al. 1999; Root et al. 2003; Wilson et al. 2005; Carroll et al. 2006; Franco et al. 2006; Hickling et al. 2006; Thomas et al. 2006; Merill et al. 2008; Sekercioglu et al. 2009). However, as with trees, it has been suggested that many species are not shifting their distributions as fast as the climate changes (Menéndez et al. 2006; Midgley et al. 2006), particularly habitat specialists and species with poor dispersal ability (Warren et al. 2001). Facilitated migration may be a practical tool for assisting the migration of some forest species across landscapes if they are unable to track rapid climate changes, provided there is little risk associated with such translocations (Hunter 2007; McLachlan et al. 2007; Hoegh-Gulberg et al. 2008).

5.2.3 Use the establishment phase to enhance diversity, reset successional trajectories, and facilitate gradual ecosystem change While most current bioclimatic zones in British Columbia are expected to simply shift northward and upward in elevation (Hamman and Wang 2006; Rehfeldt et al. 2006), scientists also expect the development of new climatic regions for which we have no current analogue (Rehfeldt et al. 2006). Under the worst-case climate-change scenario, where greenhouse gas emissions are minimally reduced (e.g., A2 family of climate-change scenarios), new climate regions start to form in parts of northern and southern interior British Columbia by 2060 and become more prominent by 2090 (G.E. Rehfeldt, pers. comm.). In these new climatic regions, ecosystems may reassemble following disturbance in new ways, as species sort themselves out in response to interactions with the novel biotic and abiotic conditions (Williams and Jackson 2007). There remains a high degree of uncertainty about how ecosystems would reassemble in new climatic regions because there are no places to look for determining what the most suitable future vegetation might be. To account for the possi-

bility that new climate regions could occur this century, management could facilitate the assembly of new ecosystems through practices that help to reset successional trajectories in ways that make forests resilient to both the present and the future climate. This could be done by:

- Planting broader and new mixes of tree species over landscapes. Planting of a broad range of species mixes over landscapes could help maintain forest productivity and resilience when the climate is rapidly changing (O'Neill et al. 2008a, b). For example, for a particular BEC site association, planting on logged sites may have a desired mean where about half of the sites are planted with 40% spruce and 50% pine, and the other half are planted with varying ratios of pine to spruce, with some of the sites planted with 100% pine and the others planted with a much greater ratio of pine to spruce. Species that did not occur previously in historical climates may also be introduced into the mixes.
- Planting species over a broader range of environments. We currently know little about how climate change will affect the ability of species to re-establish in different locations, or how varying responses to change in different locations will affect species interactions. Redundant plantings of species (and populations) over a range of climatic and edaphic conditions, including those outside the boundaries of historical geographic ranges and preferred/optimal habitats, will not only hedge against the risk of losing management investments, but monitoring at these sites will likely provide valuable information about future patterns of survival, growth, and forest productivity (e.g., Millar et al. 2007; O'Neill et al. 2008b).

Model projections and field studies (including monitoring programs) will provide insight into the range of species (i.e., distributions of variability) that may occur in new environments. Planting mixes of tree species over landscapes is also expected to reduce the probability of catastrophic forest disturbance and could provide important seed sources of better-adapted populations to revegetate sites following "natural" disturbance (Millar et al. 2007).

Enhancing tree diversity in these ways is not meant to imply an "anything goes" strategy for management. Actions should be deliberate, strategic, and guided by the best available science regarding the appropriate amount of variability in practices needed to minimize ecosystem vulnerability to climate change. Such a "risk management portfolio" should be informed by historical distributions of forest conditions, model projections about a distribution of plausible future forest conditions, as well as supporting information obtained through well-designed monitoring programs and experimental trials.

5.2.4 Promote landscape connectivity Migrating to more suitable habitats is a key way that plants and animals adapt to changing environmental conditions. While forestry activities could actively translocate important tree species by planting them on logged sites (see Section 5.2.2), forest management that promotes landscape connectivity might facilitate the migration of other organisms (Hulme 2005), particularly those with shorter lifespans (e.g., herbaceous understorey plants), and those that are more mobile (e.g., animal seed dispersers) than most long-lived trees. This could be done through forest management activities that develop landscape structures having few physical and biotic impediments to species migration.

Noss (2001) has suggested that maintaining habitat linkages running parallel to climatic gradients (e.g., latitudinal and altitudinal) and minimizing artificial barriers would be a prudent strategy under any climate-change scenario. However, if migration along corridors is unlikely to keep pace with projected change for many species (Pearson and Dawson 2005), these kinds of conventional large-scale corridors are not only difficult to justify on the grounds of climate change but also difficult to implement operationally. Rather than focus on corridors, Millar et al. (2007) suggest that managers could simply consider planning at large landscape scales to reduce fragmentation and maximize landscape connectivity. However, the tradeoff here is that these actions could make some forest landscapes more vulnerable to future disturbance.

5.2.5 Retain or restore areas buffered against climate change Ecologists suggest that some ecosystems may be buffered against the direct effects of climate change. If these kinds of "climate refugia" could be identified, managers should consider them areas for long-term retention of plants and animals that could provide a source of propagules for new forest ecosystems (Millar et al. 2007). During historical periods of rapid climate change, refugial populations have persisted on local sites buffered by extremes of regional climate changes (Huntley and Webb 1988). In topographically diverse areas, it is possible that colder microclimates may help maintain species assemblages different from those adapted to the dominant regional climate. Efforts to conserve mangrove ecosystems in the southern United States have identified areas where these ecosystems have a high probability of persistence despite climate change (McLeod and Salm 2006) and have proposed restoration programs if the ecosystems are highly degraded in these areas.

5.3 Continuous Improvement

By encouraging an array of practices that maintain ecosystem complexity within a particular ecological zone or across ecological zones in a landscape, resilience-based forest ecosystem management provides a means for minimizing the risks of abrupt and catastrophic climate-induced losses of ecosystem services that cannot be anticipated. It will also be a strong platform for implementing active adaptive management where land managers can learn from management practices that generate surprising outcomes. However, forest management frameworks must be flexible to permit timely responses to management practices and the incorporation new scientific information about ecosystem responses to climate change, as it becomes available. In British Columbia, this will require many existing forest and management practices, policies, and guidelines (e.g., the implementation of landscape-level planning, species selection and seed transfer guidelines, free-to-grow policy) to be re-evaluated through change-management processes with a climate-change lens.

5.3.1 Forecasting future forest conditions A critical aspect of managing forests will be to reduce uncertainty about the future forest conditions through forecasts that identify ecosystems and ecosystem services most vulnerable to climate change over a given timeframe (e.g., by 2050). Recent biogeoclimatic envelope modelling results provide a first approximation about the potential shifts in tree species geographic ranges and the future location of ecological zones (McKenney et al. 2006; Wang and Hamman 2006).

While we can begin to plan, at a high level, around these initial findings, approaches to forecasting climate-change impacts on ecosystems should also consider greater complexity in ecosystem responses to climate change. Current forecasting approaches rely on climate averages (or normals), making it difficult to detect non-linear ecosystem dynamics, or threshold effects, that could trigger abrupt ecosystem change (e.g., Woods et al. 2005). Future forecasts will also need to consider the importance of species interactions and the confounding effects of human land-use activities. Forecasts of future forest conditions and several lines of research could be pursued to anticipate thresholds and forecast potential trajectories of ecosystem change:

- Historical information from extreme climate effects may provide some information about cumulative responses to climate conditions outside the bounds of recent history (i.e., ecosystem and species responses to historical extreme events such as documented episodes of drought, changes in snowpack, rainwater runoff, seasonal flooding).
- Delineate bioclimatic envelopes and project changes. Based on presence/absence data, bioclimatic envelopes can be delineated for an array of species, ecosystems, and disturbance types (e.g., insect and disease outbreaks), using historical climate data obtained from weather stations. Using an array of potential climate-change scenarios, changes in the climate envelopes for species, ecosystems, or disturbance types can be projected into the future. They should include projections of no-analogue climate zones that have high potential to generate new species assemblages.
- Develop process-based models of species range shifts and ecosystem change (Kimmins 2008; Nitschke and Innes 2008). While bioclimatic envelope modelling of individual species can provide hypotheses about the general nature and extent of change, they do not account for complex interactions among species nor do they provide an understanding about the underlying mechanisms of change in species ranges or ecosystem shifts.
- Combine ecosystem process models with spatial landscape models. Linking ecosystem process models to spatially explicit landscape models (e.g., NetLogo; LANDIS- II, LLEMS) (Wilensky 1999; Mladenoff 2004; Seely et al. 2008) could improve landscape-level planning. Such linkages permit simulation of ecological processes (e.g., tree growth, succession, disturbance cycles, dispersal) that interact over various scales of time and space (He et al. 1999) and with human-imposed changes to landscapes (exotic species invasions, forestry activities, and climate change).

Ecosystems are complex and while forecasts about potential climate change impacts are challenging, they are critical for achieving sustainability goals in a changing climate. However, given uncertainty about the degree and rate of climate change, and uncertainties about the future demands society will place on ecosystems, scientists will be able to make forecasts about only a plausible range of ecosystem responses for a given a set of climate-change and socio-economic scenarios (Costanza 2000b).

5.3.2 Experimentation and monitoring Long-term strategic monitoring programs should be developed: that is, establish long-term research installations to monitor the sensitivity of species and ecosystems to climate varia-

tions. Monitoring programs should be developed with an experimental design sufficient to at least determine correlations but ideally to determine causality between climate parameters and species or ecosystem responses. The following are some examples of empirical research that could help detect mechanisms of climate-induced ecosystem changes.

- Study population responses to climate change with a focus on growth, reproductive processes, recruitment rates, mortality, and demography, particularly for ecologically significant (keystone and dominant) species and economically important species.
- Conduct research comparing tree species growth and regeneration at the margins of species ranges (i.e., southernmost and lower elevations where diebacks due to climate are most likely) with the same population processes in core parts of the range.
- Study change in ecosystem transition areas (i.e., ecotones), where rapid responses to climate change are likely.
- Monitor changes in key processes (e.g., nutrient and hydrological cycles) for vulnerable ecosystems, and measure their effects on vegetation (e.g., Herbert et al. 1999).
- Monitor changes in hydrologic regimes, such as shifts in seasonal precipitation patterns (i.e., rain vs. snow) and changes in precipitation intensity, in relation to their impact on ecosystems, vegetation, and tree growth.
- Extend traditional provenance testing to study population survival, growth, and productivity from a broader array of genotypes and species planted over a range of regional climates (e.g., O'Neill et al. 2007).
- Develop experiments (e.g., planting and silvicultural trials) that test management approaches for enhancing resilience or facilitating "ecosystem change" that can be applied at the stand level and over larger landscape areas if successful.

5.4 The Link between Climate Change Mitigation and Resilience-based Ecosystem Management

Continued efforts to reduce the atmospheric concentrations of CO_2 and other greenhouse gases are necessary to slow, or mitigate, the rate of climate change and minimize the potential adverse effects on ecosystem services. Forest management can contribute to slowing the rate of climate change at global and regional scales over the longer term by sequestering carbon and reducing greenhouse gas emissions. In addition to afforestation, and expanding the use of forest products that replace fossil fuel CO_2 emissions, enhancing carbon sequestration in forests could be achieved through various forest management activities such as longer harvest rotations, partial harvest systems, minimizing soil disturbance, densely reforesting sites with planting stock that is better adapted to local climate conditions, and reducing losses due to tree mortality caused by wildfires, insect outbreaks, and disease epidemics (Canadell and Raupach 2008; Malmsheimer et al. 2008). Forest management to mitigate climate change is strongly linked to the adaptation of current forest practices aimed at enhancing ecosystem resilience; for example, diverse practices that reduce forest vulnerability to future disturbances, in turn, play a role in mitigating climate change (Kurz et al. 2008a). Therefore, landscape-level and regional planning to enhance ecosystem resilience has strong feedbacks to larger-scale climate change, and these two aspects of coping with climate change should be considered together.

The ecological literature related to forests and forestry is among the most complex and controversial areas of scientific investigation in natural resource management. Every year, hundreds of papers are published and we have only briefly been able to introduce and discuss a small number of them in this Technical Report. Moreover, there is no general synthesis that exists in the ecology, forest management, and climate-change literature that adequately forms a "ready made" program for us to simply follow. Resilience or complexity theories, in their original forms, were not developed to address the challenges climate change presents to forest ecosystems, species, and their populations. Nevertheless, they do provide important general frameworks for us to build upon as the theories recognize the importance of large-scale environmental changes in ecosystem management and the complexity of ecosystem responses to climate change. New scientific work appears daily in the literature, and more information will become available that better incorporates ecology, population biology, and climate change with resilience theory and complex systems science. Regardless, we do have adequate first approximations of how climatic averages in the province may change in the next 20–30 years. Therefore, we can begin to plan around the projected "mean shifts," but will need to manage for a greater range of variability that will bring with it some trade-offs regarding the provision of ecosystem services.

Implementing a resilience-based approach to forest management, through practices that maintain or enhance ecosystem complexity and response diversity to climate change, involves applying a diverse array of practices over various scales of time and space, and ecosystem types. This Technical Report provides some general direction for managing forest ecosystems in a changing climate but was not intended to set out specific prescriptions. Some of the direction provided is not vastly different from what was being proposed before climate change, and its potential ecosystem impacts, was widely acknowledged. For example, emphasis was being placed on the conservation of biological diversity and the maintenance of forest structures generated by natural disturbance regimes (Forest Practice Code, Biodiversity Guidelines in British Columbia, the Convention on Biological Diversity, Sustainable Forest Management Networks, certification schemes, various criteria and indicators, initiatives, etc.). However, what is fundamentally different and new is the idea that managing for variability beyond what is prescribed by historic disturbance regimes (e.g., facilitated migration of populations, and new species mixes in novel climates that develop in British Columbia) may be necessary to maintain ecosystem resilience to climate change. This new kind of "risk management portfolio" approach to forests management may not only reduce ecosystem vulnerability to climate change but also help land managers cope with greater uncertainty about the outcomes of forest management practices.

Managing for ecosystem resilience to climate change will come with a number of challenges. The largest challenges facing managers will revolve around setting landscape-level objectives for desired future forest conditions and making the necessary policy adjustments needed to implement these resilience-based management approaches, some of which are already under

way in British Columbia (e.g., adjustments to seed transfer standards). Moreover, in some locales, rapid climate change may overwhelm efforts to manage for ecological resilience and, in these cases, societies must simply accept that climate change will cause the losses of some ecosystem services and adapt in the same kinds of ways that they have dealt with climatic variability through history: by way of societal innovations, flexibility, and diversification (Spittlehouse and Stewart 2003; Adger 2005; Namkoong 2005; Spittlehouse 2005).

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British Columbians depend on the diversity of their forest ecosystems for a wide variety of ecosystem services to enhance their well-being. Ecosystem services are the benefits that people obtain from ecosystems. They include the services that directly benefit society (provisioning, supporting, cultural services) as well as regulating ecosystem services required to maintain them (see below; adapted from Porras 2005 and Rodriguez et al. 2006).

Ecosystem Services

Regulating Services

- Carbon sequestration and climate regulation
- Nutrient cycling
- Soil formation
- Natural disturbance regimes
- Primary productivity

Provisioning Services

- Food
- Wood and fibre
- Pharmaceutical precursors
- Energy
- Etc. …

Supporting Services

- Water and air purification
- Pollination
- Flood regulation
- Pest and disease control
- Wildlife habitat
- Etc. …

Cultural Services

- Recreation experiences
- Cultural/Spiritual inspiration
- Scientific discovery
- Etc. …

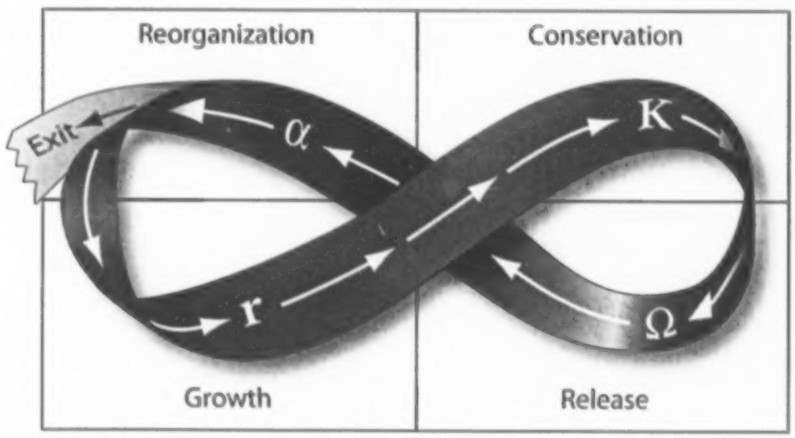
The ecological literature defines resilience in two very different ways, reflecting different aspects of ecosystem stability. The first, and more traditional, definition uses the term to describe the time it takes for an ecosystem to recover to a quasi-equilibrium state following disturbance (Pimm et al. 1984, 1991; Mitchell et al. 2000) and is sometimes called "engineering resilience" or "elasticity"(Holling 1995; Kimmins 2004). Recognizing that ecosystems may shift among domains of attraction, theoretical ecologists influenced by complex systems science defined resilience in a second way: *"the capacity of ecosystems to absorb disturbance without collapsing into a qualitatively different state that is controlled by a different set of [ecological] processes."* The two definitions of resilience have very different consequences for understanding and managing complexity and ecosystem change. Exclusive emphasis on the first definition, engineering resilience, reinforces the notion of a single stable state, that the variability of ecosystems can be effectively controlled through management, that the consequences of these practices are predictable, and that sustained maximum production is an attainable and sustainable management goal (Gunderson and Holling 1992). Complex systems scientists argue that sustainable relationships between people and forest ecosystems requires focus on ecosystem resilience. This represents a profound shift in thinking that acknowledges conditions far away from any single stable ecosystem state, uncertainty about the impacts of environmental change on ecosystems (including the outcomes of management practices), and the potential for rapid, unexpected, and irreversible ecosystem shifts that cause catastrophic losses of ecosystem services. It also focusses management on maintaining ecosystem function (i.e., ecological resilience) rather than efficiency of ecosystem function (i.e., engineering resilience), although the latter does play a role. A complex systems perspective that emphasizes the interplay between the stabilizing and destabilizing influences on ecosystems is becoming increasingly important given climate change, declines in biological diversity, and significant human-induced alterations to landscape patterns. In this Technical Report, we take a complex systems view of resilience and use the second definition.

Gunderson and Holling (2002) propose the notion of a four-phase adaptive cycle to help organize our ideas about the dynamics of complex systems and ecological resilience. The adaptive cycle describes how ecosystems change, not in a way that is completely predictable but not in way completely uncertain either. Ecosystems develop from the growth phase (*r*) to the conservation phase (*K*) along relatively slow and predictable successional pathways where slower-growing and long-lived species of the conservation phase out-compete species of the r-phase.

A key feature of the adaptive cycle is the existence of brief periods during which significant ecosystem changes can occur: the release (Ω) and reorganization (α) phases. A largely unpredictable disturbance rapidly moves ecosystems into a reorganization phase where species from on-site or distant population sources colonize newly available habitats, with those best able to adapt to the new environment taking hold. Transition from the reorganization phase to the growth phase can mark the beginning of another trip through the adaptive cycle, or the beginning of a new adaptive cycle, a change in ecological regime, and a qualitatively different ecosystem state. What emerges during the reorganization phase may be highly uncertain.

Ecological resilience is lowest during the reorganization phase when the chances of novel species entering the system is high. Biota of the growth phase are well adapted to highly variable and uncertain environments and, therefore, resilience to subsequent disturbance remains high. As the system transitions toward the growth phase where species interrelationships, interactions, and interdependencies become increasingly strong, resilience decreases, because even small disruptions to this complex system could generate major ecosystem changes.

Greater detail about adaptive cycles, and how nested adaptive cycles regulate ecological resilience, can be found in the book entitled *Panarchy: Understanding Transformations in Human and Natural Systems* (Gunderson and Holling 2002) and at the Resilience Alliance website (www.resalliance.org).



Adapted from Gunderson and Holling (2002).